Thin-Walled Structures 119 (2017) 371–384

Contents lists available at ScienceDirect

Thin-Walled Structures

journal homepage: www.elsevier.com/locate/tws

Full length article

Internally nested self-locked tube system for energy absorption

Kuijian Yang[a], Yuli Chen[a,b,*], Shoubin Liu[a], Chuan Qiao[a,c], Jialing Yang[a]

[a] *IRIMS, Institute of Solid Mechanics, Beihang University, Beijing 100191, China*
[b] *State Key Laboratory for Strength and Vibration of Mechanical Structures, Xi'an Jiaotong University, Xi'an 710049, China*
[c] *Department of Mechanical Engineering, McGill University, Montreal, Canada QC H3A 0C3*

ARTICLE INFO

Keywords:
Energy absorption
Internally nested tube
Plastic hinge model
Self-locked system
Thin-walled structure

ABSTRACT

For energy-absorbing systems constructed by round tubes, boundary constraints and/or inter-tube fasteners are required to prevent splashing of tubes from lateral loadings, which results in extra labor and time costs. To overcome this shortcoming, the self-locked system comprised of dumbbell-shaped tubes was recently proposed, which can prevent the lateral splashing of tubes under impact loadings without any constraints. To improve the energy-absorbing capacity of the self-locked system, the internally nested self-locked system is proposed, of which the basic unit is a dumbbell-shaped tube nested by round tubes inside. The proposed nested self-locked system not only inherits the self-locking effect of dumbbell-shaped tubes, but also significantly improves the energy absorption properties. In order to estimate the energy absorption of the proposed tube, a plastic hinge model is developed based on the analysis of the four-phase deformation process of the tube. Besides, experimental study and FEM simulations are also carried out, and the results agree well with the theoretical prediction. Furthermore, the geometric parameters of inserted round tubes and the stacking arrangement of the proposed nested self-locked systems are investigated, and suggestions on designing an internally nested self-locked energy-absorbing system are provided for practical applications.

1. Introduction

Sudden impacts and blast loadings may cause great damage to lives and properties [1], and accordingly, energy absorption devices play important roles in many engineering fields [2]. For instance, in the field of vehicle engineering, energy absorbers are applicable to vehicle seats [3], passenger compartment of cars [4] and motorcycle helmet [5]. However, the application of energy-absorbing systems is limited by cost and space. In order to satisfy the constraints in practical applications, it is in great demand to reduce the cost and improve the efficiency of energy-absorbing systems.

Metallic thin-walled round tube systems have attracted extensive attentions from researchers due to its easy manufacturability, low cost, and high specific energy absorption [6–10]. Most of the research focused on the force response and energy-absorbing behavior of round tube systems under compression [6,7], and some also investigated the effect of elastic waves and impact velocity [8,9]. Recently, researchers have transferred their attention to improving the performance of round tube system by novel geometry design. Niknejad et al. investigated the energy absorption capacity of corrugated tubes through experimental study [11]. Olabi et al. proved oblong tube to be an ideal structure under compression [12]. Morris et al. studied the quasi-static lateral compression of nested systems with different indenters and exterior constraints by both experiment and numerical simulation [13]. Wang et al. proposed a theoretical model of nested systems based on rigid, perfectly plastic material idealization [14]. Composite tube systems have also drawn attention from researchers due to weight saving. El-galai et al. confirmed that carbon/epoxy tubes display excellent specific energy absorption capacity [15]. Fan et al. and Torre et al. evaluated energy-absorbing properties of sandwich tube systems by impact testing experiment [16,17]. Niknejad et al. and Abedi et al. investigated foam-filled columns with different cross section under axial compression [18,19].

Modifiability is an indispensable requirement for energy-absorbing systems in emergency because it is important to respond quickly to the need of impact protection. However, round tube systems require extra labor and time costs during installation for positioning structures and boundary constraints, which results in the lack of modifiability to respond quickly to the need of protections in emergencies. To meet this design requirement, Chen et al. recently proposed a novel self-locked energy absorbing system, in which tubes can interlock with each other under compression and avoid secondary damage [20,21]. However, this self-locked system did not make best use of space, which suggests the energy-absorbing capacity could still be improved. In this paper, an efficient internally nested self-locked energy-absorbing system is proposed. The basic unit of this system is the nested self-lock tube,

---

[*] Corresponding author at: IRIMS, Institute of Solid Mechanics, Beihang University, Beijing 100191, China.

http://dx.doi.org/10.1016/j.tws.2017.06.014
Received 22 March 2017; Received in revised form 22 May 2017; Accepted 14 June 2017

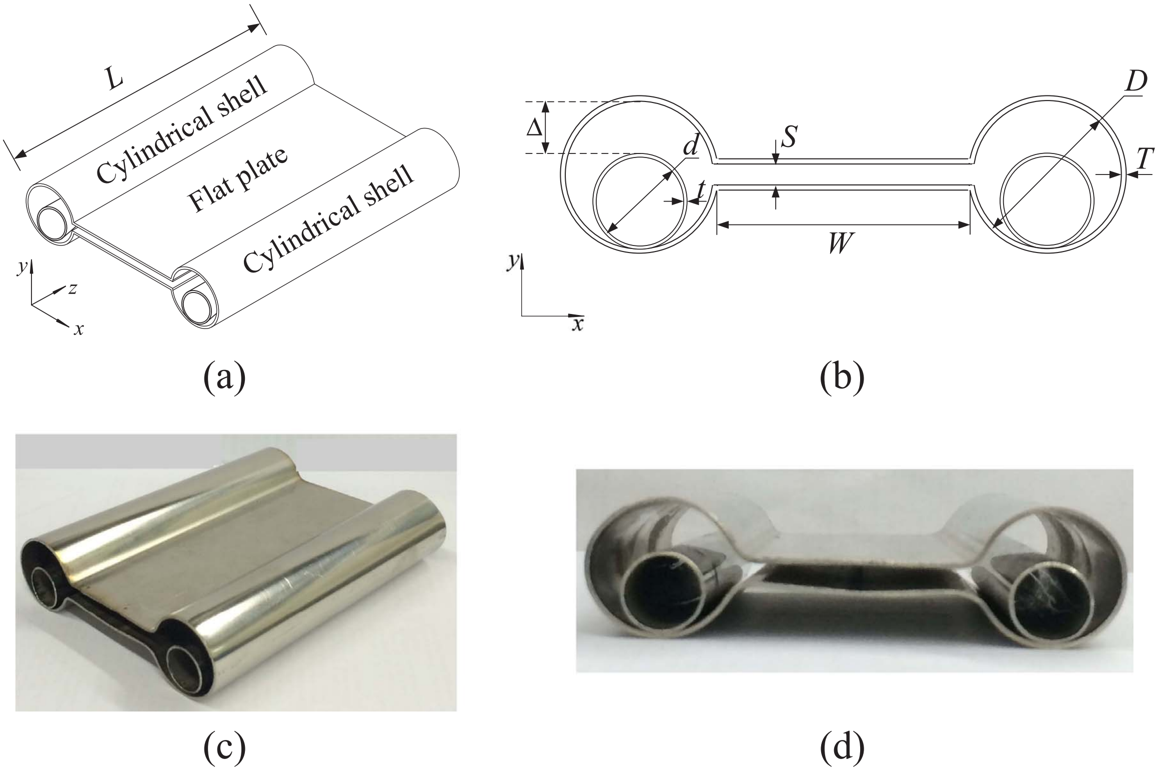

Fig. 1. Model of a nested self-lock tube from (a) normal view and (b) side view, and experiment specimen from (c) normal view and (d) side view.

comprised of a dumbbell-shaped outer tube and two small round inner tubes. A theoretical model is proposed to investigate the deformation process of a single nested self-lock tube, which is also validated by experiments and finite element method (FEM) simulations. Besides, the effect of geometric parameters and stacking arrangement on the energy absorption properties of nested self-locked systems are investigated, which provides valuable insight and guidelines for the design of energy-absorbing systems.

2. Nested self-locked system

2.1. Geometry of nested self-locked system

In order to achieve both flexibility and efficiency, an internally nested self-lock thin-walled tube is proposed here as shown in Fig. 1. The nested self-lock tube is constructed by an outer tube with dumbbell-shaped cross section and two small round inner tubes. The outer tube is comprised of two open cylindrical shells and two parallel flat plates, and the geometry is determined by 5 parameters as shown in Fig. 1: the length L, the width of the flat plates W, the spacing between the flat plates S, the thickness T and the mean diameter D. Here the mean diameter D is the average of the external and internal diameters of the cylindrical shell. The inner tube has the same length as the outer tube, and its geometry is defined by the mean diameter d and the thickness t. The maximum spacing between outer and inner tubes is define as Δ, and $\Delta = D - d - T - t$.

In this paper, the shape of the dumbbell-shaped outer tube can also be characterized by normalized geometry parameters, i.e. the normalized width of the flat plates $\overline{W} = W/D$, the normalized spacing $\overline{S} = S/D$, and the normalized thickness $\overline{T} = T/D$. Similarly, the normalized mean diameter and thickness of the inner tube are $\overline{d} = d/D$ and $\overline{t} = t/D$, respectively, and the normalized spacing between tubes is $\overline{\Delta} = \Delta/D = 1 - \overline{d} - \overline{T} - \overline{t}$.

A nested self-locked multiple-tube system can be assembled by stacking the single tubes in a staggered arrangement as shown in Fig. 2(a). By this arrangement, tubes can interlock with each other under compression and thus provide lateral constraint to avoid splash and secondary damage [20].

2.2. Efficiency of nested self-locked system

The self-locking effect and energy-absorbing efficiency of the proposed nested self-locked system, the widely-used round tube system, and the ordinary self-locked system without inner tubes are glanced in this section. The material and wall thickness of the tube in the three systems are the same. The geometric parameters of a single tube in the three systems are provided in Table 1, and the total tube number, mass and volume of the systems are listed in Table 2. The results are obtained by FEM simulation with ABAQUS/Explicit. The plane strain element CPE4R is adopted because the tube length is much larger than the dimensions of tube cross-section. The energy-absorbing system is placed between two rigid plates. The lower plate is fixed, and the upper plate impacts the system with a mass of 70 kg and an initial velocity of 10 m/s. The contact properties between surfaces are set as “surface to surface”, “penalty 0.05” and “hard” contact [14,20]. A bilinear elastic-plastic constitutive model is employed in the simulations for all the tubes, with material properties same as those in Section 4.1.

The comparison of the three systems is made in three aspects: deformed configuration, mass specific energy absorption SEA_m and volume specific energy absorption SEA_V. Here the mass specific energy absorption SEA_m is defined as the energy absorption per unit mass [20,22]

$$SEA_m = \frac{EA}{m}, \tag{1}$$

and the volume specific energy absorption SEA_V is defined as

$$SEA_V = \frac{EA}{V} \tag{2}$$

where EA is the energy absorption at 70% compression ratio.

The deformed configurations of these three systems at 70% compression ratio are depicted in Fig. 2. The nested self-locked tube system